PHYS4029P

Theoretical Physics Group Project

Course Guide 2025/2026

Version 1 — Dec 9, 2025

University of Glasgow

Contents

Part 1

General information and guidance

1.1 General information and contacts

This guide is intended for students enrolled on the **PHYS4029P Computational Physics Group Project Course**.

The course begins on the Tuesday of Week 1 at 1100 with an Induction lecture (rm 217A, Gilmorehill Halls). The projects themselves then begin at 1200 that day. The class then runs 1100–1700 on Tuesdays and Thursdays in 220A through to the end of Week 9.

1.1.1 Communication

All information about the lab classes will be communicated via the PHYS4029P Moodle. Provided you have enrolled on the course in MyCampus, you will automatically be enrolled on the Moodle. Please check the Moodle regularly for new information:

(https://moodle.gla.ac.uk/course/view.php?id=53096)

1.1.2 Contacts

Course Head:	**Individual group supervisors**
Sophie Renner (Room 534) sophie.renner@glasgow.ac.uk	Olivia Simon o.simon.1@research.gla.ac.uk Mairi Gilmour m.gilmour.2@research.gla.ac.uk Ben Smith b.smith.4@research.gla.ac.uk

1.1.3 Acknowledgements

Thank you to Dr Robert Bennett and Dr Dave Sutherland for providing these course materials, and to the excellent demonstrators who have helped to run and shape this course.

1.2 Code of Professional Conduct in the Laboratory

Our aim is to provide a safe and enjoyable learning experience for all students in the laboratory, whether that is face-to-face or remotely. Whilst we, as staff, will do everything we can to help with this, students also have an important role to play in ensuring that this is achieved. We would specifically like to highlight the following points:

1. The laboratory is a professional working and studying environment. We therefore expect you to behave in a professional manner towards one another and towards the lab demonstrators and staff at all times
2. Follow all safety instructions, in terms of both general good practice and with regard to experiment-specific points. This is critical both for your own health and for that of your fellow students. Specifically, safety instructions given by technicians or the lab demonstrators must be adhered to.
3. We value the diversity of our student body and recognise that this diversity improves the quality of our work by allowing students to bring a range of skills and viewpoints to inform and enhance their collective achievements. We therefore expect that students will work productively and professionally together in an atmosphere of mutual respect.
   (a) With this in mind, any form of bullying and harassment — such as on the basis of any personal characteristic (including, but not limited to: nationality, race, disability, gender or gender identity, religion [or proxies for this, e.g. football team allegiance], sexuality, appearance, or age) — is unacceptable.
   (b) Please avoid at all times potentially offensive "banter" with your fellow students, which may be hurtful and problematic for some, including those who witness it. Please note that claiming something was "banter" is in no way an excuse for bullying or harassing behaviour.
4. Any reports of bullying, exclusion, or discriminatory behaviour will be taken very seriously by the School of Physics and Astronomy. If anyone wishes to report any untoward behaviour, speech or social media content from any person or group of people in the laboratory, they may do so in confidence to the laboratory head, his/her deputy, to the School Equality and Diversity officers (currently Angela Eden, Fiona Grant, and Jonathan Taylor), or (in the case of staff) to a trade union representative. All such concerns will be treated seriously and in confidence. (This includes incidents where students or staff are the targets or the perpetrators of such behaviour).
5. Some of these points are also included in the University of Glasgow Dignity at Work and Study Policy and the Code of Student Conduct and can result in disciplinary proceedings, where appropriate.
   For further information see:
   https://www.gla.ac.uk/myglasgow/humanresources/equalitydiversity/policy/dignityatwork/
   and
   https://www.gla.ac.uk/myglasgow/apg/.

1.3 The intended learning outcomes of PHYS4029P

By the end of the PHYS4029P course, you will be able to ...

- programme straightforward procedures in a high level computer language;
- analyse and interpret computational data and make a critical assessment and draw valid conclusions from the results of computational investigations;
- apply computer software to analyse computational data and to write scientific reports;
- apply logical analysis to problem-solving;
- interact positively with colleagues in a group context;
- apply team-working skills to address a complex physics problem and contribute significantly to the work of a group tackling such a problem, combining your own work constructively with the work of others;
- contribute to the management of a group engaged in project work;
- combine with colleagues to prepare and deliver a presentation and report of group work;
- appreciate open problems typical of business situations.

1.4 How PHYS4029P will work

1.4.1 Choosing your project

We are offering three Group Projects this year, see Table 1.1. Students must submit their preferences for Projects via Moodle by 1600 on Day 1 of Semester 2, according to which the projects are then allocated, and begin on Day 2 of Semester 2. Detailed guidance for each project is given in Part 4 of this document.

Title	Field	Group size	Supervisor
A: Relativistic Stars	Mechanics/relativity	3 or 4	Olivia Simon
B: Chaos in the double pendulum	Mechanics	3 or 4	Mairi Gilmour
C: Dynamics of a wavepacket	Quantum mechanics	3 or 4	Ben Smith

Table 1.1: Projects offered this year

1.4.2 The Course timetable

PHYS4029P meets on Tuesdays and Thursdays, 1100-1700. You are expected to put in the equivalent of around 5 hours' worth of work per six-hour session. Lunch and regular breaks are essential! There is no specific timetable within each day, though, and each project is unique. Your Project Supervisors will outline their expectations when you first meet them

Table 1.2 outlines the key dates for the course.

1.4.3 Role of supervisors and the groups

The supervisors are there to oversee your work and discuss with you about your direction and plans for the next steps of your work. They will not be in the lab at all times, and are not there to guide you at every step or to provide large amounts of detailed technical support.

Week	What
1: Tuesday 1100-1200	Induction lecture
1-8:	Group project work is carried out
7/8:	Individual presentations
9: Thursday at 1700	Group report deadline
10: Thursday at 1700	Individual report deadline
11: Thursday 1100-1700	Group presentations

Table 1.2: Timetable

Part 2

Carrying out your research project

Each assigned project has both theoretical and computational aspects. You are presented with different physical problems that you will solve both analytically and numerically for problems that are analytically tractable, and only numerically for problems which may not have an analytical solution in closed form. You are supposed to develop the software package as a group effort which implements the numerical solution of the problems you are given.

2.1 Team organisation

Team roles

This project requires you to work as a team and manage a collaborative computing project. All members of the team should work on the code (it is not enough to **just** be the presenter of the group presentation and/or the editor of the group report, but it **is** expected for example that a particular team member might be less deeply involved with the code than others and more concentrating on presentation). You should work as a team and manage a collaborative computing project. As part of your report you need to present a diagram of your software package code flow indicating the person or persons that worked on each item.

Team dynamics

You should assign roles as early on as possible. Each of you has to contribute to a distinct part of the code and be able to explain what is its context, its goal, why this particular logic was used and what its output is.

Again, it is not enough to work only on the group presentation and the group report. Each of you has to be able to check out the code, compile it, run it, produce the plots and numbers. Though you will focus on your on a specific part of the project, you have to learn about the other parts of the projects from your colleagues.

Time management

While the total project lasts for 10 weeks, you should schedule a full week to prepare your individual talk and implement the comments from your supervisors to it.

Another week will be spent on your individual report and another for your group talk or group report. The error analysis of your software could also well take a week to perfom. The first week is just the introduction to the lab, while the theoretical solution takes you the following week. It means there are only four weeks remaining to do the actual software coding for the basic problem and then find ways to improve it.

Time flies quickly, so please plan accordingly. Divide tasks in the group. You will meet your supervisor every week to follow your progress and to answer questions. If you encounter difficulties at any time that you cannot easily overcome, seek help from your project supervisor.

All the information above probably seems daunting, so here's an example of how a project might be carried out;

Example of division of labour: Baking a cake

Imagine that your team (Alice, Bob, Carrie and Darth) has been tasked with baking a cake. Distinct roles might include;

- Alice: Measurer of ingredients
- Bob: Mixer of ingredients
- Carrie: Oven timer
- Darth: Serving to customer

But there's a problem — Darth's role on its own is *not* enough as he hasn't really taken part in baking the cake which is the task to be completed as a group. Alice and Bob's roles *would* be enough as they have done something fundamental to the cake, while Carrie's is debatable. Nevertheless, Alice and Bob might be overworked and none of this is fair on Darth, so a better division of labour might be;

- Alice: Measurer of wet ingredients, turning on the oven
- Bob: Main mixer of ingredients, turning off the oven
- Carrie: Oven timer, mixing assistant, egg cracker
- Darth: Measurer of dry ingredients, serving to customer

Now while all team members still have distinct roles they can talk about in their report and presentation, each one will still have a knowledge of the fundamentals of baking the cake. They will know what the other team members are doing, and know how the parts of the process fit together.

2.2 Project stages

2.2.1 Comparing analytical and numerical solutions to physical problems

To understand the physics, the first task in all the projects is to solve systems both analytically and numerically, and to compare the results. This will also validate your numerical software package. Develop the code to be modular and generic, so that it allows you to adapt and extend the code later. To guide you through the process here are an outline of steps you are expected to go through:

- Solve the problem analytically using the assumptions given

- Solve the same system numerically
- Plot the analytic results and numerical results separately
- Quantify the accuracy of the numerical method as the absolute difference between the exact analytical value and the approximate numerical solution
- Study how the precision of your numerical method increases as you decrease, for example, the step size in space or time
- Quantify how the difference in results between two consecutive steps, the CPU consumption, and the computation time vary with the precision of the simulation.

2.2.2 Using numerics for problems without (simple) analytical solution

Now that you have sorted out the simplest case and are equipped with a code that solves a generic problem, it is time to investigate some more systems that are not so amenable to analytic calculation, but which are used in real physics applications. Of course, no analytical solution is possible to these more complex cases, so only the numerical solution should be presented.

- Solve the system numerically
- Quantify how i) the difference in results between two consecutive steps, ii) the CPU consumption, and iii) the time vary with the number of iterations.

2.2.3 Extending the functionality of your simulation code

For maximum grades, you need to go beyond these tasks. You can develop the software to solve even more generic systems, or evaluate better the precision of the software, or improve the numerical simulation to be more accurate, faster, or both, to improve the user-friendliness.

Here are some examples of further extensions of the functionality that can be implemented:

- Alternative numerical methods for solving differential equations.
- Any non-uniform, adaptive grid (mesh) spacing. In a real life example, one would use a fine grid in regions of rapid changes and larger steps in regions where the system is smoother.
- Any boundary conditions drawn pixel-by-pixel.
- Any arbitrary boundary conditions and/or initial conditions given with some pre-defined commands.
- A user interface, e.g. in `C++`, `Qt` or similar, for the user to provide the input parameters and display the results and plots.
- Further profiling and performance evaluation of the program, to quantitatively compare different numerical methods or grid sizes.

2.3 Frequently-asked questions

- Q: Do we have to use a particular programming language to do our project?

  A: No, you can choose whatever you like, as long as you write the code yourself.

A popular choice for scientific computing is Python. **Important: using symbolic algebra/numerical software packages such as Mathematica or Maple is not acceptable for this course**, although if appropriate you can of course use such tools to check the results of your self-written code. Using numerical analysis libraries (such as SciPy for Python) is completely ok, and encouraged. There *is* a fine line here, so if you're not sure whether what you're doing constitutes 'writing code yourself', then consult with your supervisor or the course head as soon as possible.

This isn't an arbitrary restriction just to make things harder. If and when you move into industry or research you'll need to be able to write your own programs, since when you're doing something cutting-edge then a pre-built piece of software like Mathematica likely won't have the right functionality built in.

- Q: We have a particular technical problem. Will the supervisor know the exact solution?

  A: The supervisors and course head have experience in scientific programming and computational physics in general, but there are so many possible technical and programming issues that your supervisor will **almost certainly not have seen a given problem before**, let alone know how to solve it. It is far more likely the supervisor will be able to use their experience of running into (different) problems to help you look for the answer to yours.

  As alluded to above, this course is meant to prepare you for what "real-life" programming is like in academia or industry, where in general you'll have to solve problems on your own. There is a *vast* amount of information on the internet about almost any technical or coding issue you might have, so that should be your first point of call, as well as the documentation for your chosen language.

- Q: Do we have to split the team into distinct roles, or can we all work on everything?

  A: You can organise your team however you like. But, you should bear in mind that you need to write an individual report and do an individual talk, so if you split the roles up you will probably find it easier to highlight how *you* contributed to the project.

- Q: Are we allowed to work on the project outside the Tuesday/Thursday lab sessions?

  A: Of course.

- Q: Should we include the source code in the reports?

  A: In general, no. Including small snippets can work well when you're explaining a particular algorithm or technique, but for example you certainly should *not* include all the source code in an appendix or similar.

Part 3

Assessment

3.1 Weightings

PHYS4029P is a 20-credit course. The overall grade for this course is split into a number of components to take account of both your individual contribution and the collective achievement of your group. The marks breakdown is listed in the table below, and the full marking criteria follow in Part 5D. The different assessment components and their weightings are

Component	Weighting	Marking
Individual oral presentation	25%	Double marked by supervisor & course head, marks manually combined
Individual written report	25%	Singly marked by course head
Group oral presentation	25%	Double marked by course heads of 4021P and 4029P, marks averaged (unless there's a >3 mark difference, then we manually combine)
Group written report	25%	Singly marked by course head

Table 3.1: Assessment components

For the group assessments, everyone in the group is awarded the same mark.

Each component will be graded on the University's 22-point scale, scaled by the appropriate weighting factor, and then added to give an overall course grade, also on the 22-point scale.

3.2 Reports

Each student is required to submit an individual report with a deadline of 1700 on the Thursday of Week 10, and each group needs to coordinate a group report summarising the achievements of the whole group. The deadline for this is 1700 on the Thursday of Week 9. This should be written so that it is understandable to a general physics audience (i.e. the course heads) and not just to specialists.

Both reports should include an introduction, a description of the analytic work and the numerical methods used, the results and conclusions. Results should be presented clearly and concisely, using diagrams where possible. Don't forget to quantify your errors, and draw appropriate conclusions. We recommend writing the report in LaTeX as it is the best way of including equations, and offers a number of useful features to comment on code. Whichever format you choose, the report needs to be of scientific quality in content and form.

Both reports have a page limit set below — this is a **maximum** not a **target**. If you can fulfil all assessment criteria in a shorter document that's also absolutely fine, the only reason there's a maximum length specified is due to the practicalities of marking.

3.2.1 Individual

This report, whilst giving a background to the whole project and summarising the achievements of the whole group, should concentrate on your own individual contribution to the project. This should be a maximum of **8 pages in length**.

3.2.2 Group

This report should detail the achievements of the whole group. This should go into detail about the background of the project, why the work is being done, and make appropriate reference to the literature. It is important that this report reads as a cohesive whole. The report should be a maximum of **15 pages in length**.

The report must include a clear statement of who worked on which parts of the code. This could be provided, for example, as annotations on a diagram showing how the different parts of the code interact, or simply as a "Statement of work" section at the end of the report.

3.2.3 Assessment criteria for the written reports

Tables 3.2 and 3.3 summarise the criteria that markers will use when assessing students individual and group written reports. The tables at the end of this document then set out in detail how the grade you will receive for each of these criteria maps to the 22 point scale.

3.2.4 The difference between the group report and the individual report

Group report

Think of your group as a small research/consultancy team within a big company. Your company has been commissioned to carry out some work (e.g. finding out the alternative ways to climate control the Scottish parliament building; investigating the sewage dispersal options for an island community; producing publicity material for the nuclear industry, or pinpointing the location of a gamma ray source) and your team has been put together and tasked to do this work. Your group report is the glossy folder you show to your client at the completion of the project. You need to remind the client what you've been commissioned to do; lay out the background and context of your work; tell them how you went about tackling the problem; what was done; how the tasks were managed; what were your findings and finally what recommendation you are putting forward (possibly with some hints that it will be a good idea for your client to you give a little bit more money to study the things they have not thought about originally). You should be spending a lot of time making sure that your work is presented clearly and in a positive light. Your next pay cheque depends on it. This report should not be longer than 15 pages and should be presented as a professional and scientific report. Remember: the client has spent a small fortune. They will want to know all the scientific details and will expect a scientific report.

Category	Criteria
Presentation, grammar, style and structure	Is the report neatly typeset with clear labelled diagrams and appropriate figure captions? Is the English correct? Is the report structured and are all the parts tied into the whole?
Abstract, introductory sections	Is there an appropriate abstract? Does the introduction explain what is being done and why? Are the relevant theoretical results quoted? Are the important features of the simulations described and irrelevant detail left out?
Main part of report	Are the results presented clearly and in a suitable manner? Is the principle of calculations presented? Is there a discussion of the meaning, significance and interpretation of the results? Has an attempt been made to compare the results with accepted values? Have the possible sources of error been considered?
Individual contribution	Is it clear what the individual student did themselves? Is it clear how the work of the individual fits into the broader work of the project?
Summary and conclusions	Are the results of the project summarised? Are sensible conclusions drawn? Are the conclusions supported by the results obtained? Has the student commented on whether the objectives have been achieved? Is there a reasonable attempt to pull all the parts together?

Table 3.2: Marking criteria for individual written reports

Individual report

Having completed the project, the various team members go back to the department/division they normally work in. You then need to submit a personal report to your line manager to let them know what you've been up to for the past three months and why you should be given a promotion based on this work. This is your individual report. Here, you should be telling your boss what was your contribution to the team project, how well the group worked together as a team and what you think you have learnt from your experience that you can bring back to your department. You should also briefly introduce the aims and context of the group project and clearly set out your contribution toward the project. Just to make sure that your boss is convinced of your work, you should not skimp on the science here. However, you should not copy and paste large chunks of the group report. Most likely, you will have some spare copies of the glossy group report, which you can attach to your personal report. Your boss is super busy. Your individual report, therefore, should not be more than 8 pages long. Having a clear structure to this report will help your boss get to the information she/he wants to find quickly. She/he can then make the decision about what project you should be assigned to next and whether you deserve a pay rise.

Category	Criteria
Presentation and written style	Is the report neatly typeset with clear labelled diagrams and appropriate figure captions? Is the English correct? Is the report structured and are all the parts tied into the whole?
Abstract, introductory section(s)	Is there an appropriate abstract? Does the introduction explain what is being done and why? Are the relevant theoretical results quoted? Are the important features of the measurements described and irrelevant detail left out?
Body of the report	Are the results presented clearly and in a suitable manner? Is the principle of calculations presented? Is there a discussion of the meaning, significance and interpretation of the results? Has an attempt been made to compare the results with accepted values? Have the possible sources of error been considered?
Summary and conclusions	Are the results of the project summarised? Are sensible conclusions drawn? Are the conclusions supported by the results obtained? Has the student commented on whether the objectives have been achieved? Is there a reasonable attempt to pull all the parts together?
Integration/structure	Does the document read as a cohesive piece? Is it clear how the work of individuals linked together to create the whole?

Table 3.3: Marking criteria for group report

3.3 Presentations

3.3.1 Individual

The group supervisors will, in consultation with each group, arrange a time towards the end of the group project for internal presentations from each group member. These will be watched by your own group supervisor and the course head. Each student in the group presents for **about 8 minutes**, followed by a couple of minutes for questions. The set of individual presentations should cover all work performed by the group with minimal overlap. The presentations are likely to be better if each group member is assigned a topic they are familiar with and have done a large fraction of the work on. The group supervisors will agree on a mark for each presentation.

3.3.2 Group: The Group Project Conference

The course heads will assess the group talks, which will be held as a joint mini-conference for all group projects (theoretical and experimental) on the Thursday of Week 11 in Semester 2 from 1100 to 1700. The two course heads (of PHYS4021P and PHYS4029P) and various supervisors will not be experts in each project area, and therefore the talks should be prepared so that each project is presented in an engaging and clear way to a scientifically educated but non-specialist audience. This should be a collective presentation to which all group members contribute to the planning thereof, and which should be presented by a subset of the team. It is not necessary that every team member speaks in the presentation, although every team member is expected to contribute to the preparation of the presentation.

The presentations should be written in LaTeX (e.g. Beamer), Powerpoint, Keynote or similar. Please make sure you have all your material first, so that you have a clear view of what the main message is of your talk. Please plan for several days of work on the presentation alone. From previous years' experience, it takes several iterations with your supervisor to get the presentation perfect. Each group will be allowed 20 minutes for their presentation.

The course heads will agree on a mark for each group and provide written feedback.

3.3.3 Assessment criteria for presentations

Tables 3.4 and 3.5 summarise the criteria that markers will use when assessing students individual oral presentations. The tables at the end of this document then set out in detail how the grade you will receive for each of these criteria maps to the 22 point scale.

Category	Criteria
Timekeeping and overall planning	Did they keep within the specified time? Is there a clear, logical structure to the presentation?
Quality of slides	Are the slides well presented – is the layout clear? Are the fonts in an appropriate size and colour? Are figures clear? Are graphs/tables/etc labelled suitably?
Clarity of oral presentation	Did they speak clearly? Did they engage with the audience?
Content	Was the scientific content well described? Was the level appropriate for the audience and the project? Is it clear how the student's work fitted into the wider project?
Answers to questions	Were they able to answer questions? If they couldn't, did they tackle that situation well?

Table 3.4: Marking criteria for individual oral presentations

Category	Criteria
Timekeeping and overall planning	Did they keep within the specified time? Is there a clear, logical structure to the presentation?
Quality of slides	Are the slides well presented – is the layout clear? Are the fonts in an appropriate size and colour? Are figures clear? Are graphs/tables/etc labelled suitably?
Clarity of oral presentation	Did they speak clearly? Did they engage with the audience? Did the work of different speakers compliment the co-presenters?
Content	Was the scientific content well described? Was the level appropriate for the audience and the project? Is it clear how the student's work fitted into the wider project?
Answers to questions	Were they able to answer questions? If they couldn't, did they tackle that situation well?

Table 3.5: Marking criteria for group presentation

Part 4

Specific projects

This part contains detailed descriptions of the four projects offered this year. As discussed in detail in section 2.2, each follows the same format;

1. **Physical background**

   Here you are given the motivation behind the project and the basic equations to be simulated.

2. **From analytics to numerics**

   (a) Problems with analytic solutions

   Here you will be asked to solve a particular problem analytically and numerically, and compare the results.

   (b) Problems without (simple) analytic solutions

   Then, you will be given problems to which there is no (simple) analytic solution, so that numerics are a must. This is meant as the 'jumping off point' for you to continue investigating the problem in whichever direction you see fit (see section 2.2.3)

A Relativistic stars

A.1 Physical background

We model a star as a self-gravitating, spherically symmetric fluid in hydrostatic equilibrium, where the force of gravity is balanced by the pressure (technically pressure *gradient*) force. Let the fluid be described by its pressure, $P \equiv P(r)$, and its density, $\rho \equiv \rho(r)$, as a function of the radial distance from the centre of the star, r. It is useful to also define $m \equiv m(r)$, the total mass enclosed within a sphere of radius r, which is calculated from the density via the continuity equation

$$\frac{\mathrm{d}m}{\mathrm{d}r} = 4\pi r^2 \rho \,. \tag{4.1}$$

Neglecting relativistic effects, hydrostatic equilibrium fixes the pressure gradient to be

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{Gm\rho}{r^2} \,. \tag{4.2}$$

For very dense stars, special and general relativistic effects can be accounted for via the Tolman-Oppenheimer-Volkoff (TOV) equation

$$\frac{\mathrm{d}P}{\mathrm{d}r} = \underbrace{-\frac{Gm\rho}{r^2}}_{\text{Newtonian}} \underbrace{\left(1 + \frac{P}{\rho c^2}\right)\left(1 + \frac{4\pi r^3 P}{mc^2}\right)}_{\text{Special relativity}} \underbrace{\left(1 - \frac{2Gm}{rc^2}\right)^{-1}}_{\text{General relativity}} , \tag{4.3}$$

where c is the speed of light.

The equations shown above are not sufficient by themselves since we have three variables ($P(r)$, $m(r)$, and $\rho(r)$). If we also know the *equation of state* (EoS) of the fluid, which fixes the pressure P in terms of the density ρ at any given point, then the differential equation resulting from hydrostatic equilibrium (be it (4.2) or (4.3)) can be solved. The initial condition is usually the density at the star's centre, when $r = 0$.

This project will solve the above differential equations to explore several possible equations of state for both white dwarfs and neutron stars.

A.2 Equations of state

Equations of state (EoS) describe relations between 'state' variables, for example, pressure, density, and temperature and are dependent on the matter content of a star. An assumption that greatly simplifies stellar structure equations is assuming that the interior of the star has a constant temperature. This results in the EoS being a function of only pressure and density (also known as the 'barotropic' condition). A simple example would be to consider a general *polytropic* equation of state, given by,

$$P = K\rho^{1+\frac{1}{n}}, \tag{4.4}$$

where K is a constant and n is known as the polytropic index, which can be used to understand some simplified stellar models. Stars at different stages of their evolution have different equations of state.

White dwarfs are supported by the degeneracy pressure of the electrons within it. Depending on how densely the electrons are packed, they may be moving non-relativistically or relativistically (crossover happens around $\rho \sim 10^6\,\mathrm{g\,cm^{-3}}$). The EoS of the white dwarf in these cases takes on the limits:

$$\begin{aligned} P &= \frac{1}{20}\left(\frac{3}{\pi}\right)^{\frac{2}{3}} \frac{h^2}{m_e}\left(\frac{\rho}{\mu_e m_p}\right)^{\frac{5}{3}} \quad \text{(non-relativistic)} \\ P &= \frac{1}{8}\left(\frac{3}{\pi}\right)^{\frac{2}{3}} hc\left(\frac{\rho}{\mu_e m_p}\right)^{\frac{4}{3}} \quad \text{(relativistic)} \end{aligned} \tag{4.5}$$

where h is Planck's constant, m_p the proton mass, and $\mu_e \approx 2$ is the number of nucleons per electron in the star. (4.5) are the limiting behaviours of the more general EoS

$$\begin{aligned} P &= (1.42180 \times 10^{25}) \times \phi(x), \\ \phi(x) &= \frac{1}{8\pi^2}\left[x\left(\frac{2x^2}{3} - 1\right)(x^2+1)^{1/2} + \ln\left(x + (1+x^2)^{1/2}\right)\right], \\ x &= (1.0088 \times 10^{-2}) \times \rho^{1/3}, \end{aligned} \tag{4.6}$$

where the numbers in scientific form are given in cgs units.

Neutron stars are supported by the degeneracy pressure of its constituent neutrons, as well as repulsive nuclear forces. Considering just the degeneracy pressure results in the EoS

$$\begin{aligned} P &= 2 \times 10^{36} \times \phi(x),\ \rho = 2 \times 10^{36} \times \frac{1}{c^2} \times \chi(x) \\ \phi(x) &= \frac{1}{8\pi^2}\left[x\left(\frac{2x^2}{3} - 1\right)(x^2+1)^{1/2} + \ln\left(x + (1+x^2)^{1/2}\right)\right], \\ \chi(x) &= \frac{1}{8\pi^2}\left[x\left(2x^2+1\right)(x^2+1)^{1/2} - \ln\left(x + (1+x^2)^{1/2}\right)\right], \end{aligned} \tag{4.7}$$

(where the numbers in scientific form are given in cgs units); more complicated models including nuclear interactions, such as the SLy and FPS EoSs, are available in tabulated form here.

A.3 The Lane-Emden equation

If the equation of state is *polytropic* as given in equation (4.4), then the non-relativistic hydrostatic equilibrium equation (4.2) and the continuity equation (4.1) combine to form a single second order ODE for the density

$$\frac{1}{\xi^2}\frac{\mathrm{d}}{\mathrm{d}\xi}\left(\xi^2\frac{\mathrm{d}\theta}{\mathrm{d}\xi}\right) + \theta^n = 0\,, \tag{4.8}$$

known as the *Lane-Emden* equation. In (4.8),

- ξ is a dimensionless radius (note: The 'surface' of a polytropic star is defined as the point where the density falls off to zero. This can happen for any value of ξ. You can then find out the physical radius of the star by appropriately dimensionalising ξ.)
- $\theta \equiv \theta(\xi)$ is related to the density via $\rho = \rho_0\theta^n$, where ρ_0 is the density at the centre of the star. The boundary conditions are $\theta(0) = 1$ and $\frac{\mathrm{d}\theta}{\mathrm{d}\xi}|_{\xi=0} = 0$. Solving the Lane-Emden equation thus gives you the distribution of density (hence matter) within the star. You can then find out the mass of the star using the continuity equation.

Task: Show that the Lane-Emden equation can be derived by combining hydrostatic equilibrium, a polytropic equation of state and the continuity equation.

A.4 Problems with analytic solutions

We start with the Lane-Emden equation, which you are supposed to solve both analytically (for some cases) and numerically. This can be used to benchmark your numerical solver.

Task: Solve the Lane-Emden equation analytically for $n = 0$, $n = 1$ and $n = 5$.

Task: Solve the TOV equation for a constant density $\rho(r) = \rho_0$. Do you think this is a physically valid solution?

A.5 Problems without simple analytic solutions

We extend to the remaining cases of the Lane-Emden equation and the TOV equation which do not have simple analytical solutions and hence you have to fully rely on your numerical solver.

Task: Solve the Lane-Emden equations numerically for arbitrary n. Which solutions are physical, and which are not?

Task: Choose a particular n (for example, from equation (4.5), you can identify the polytropic index for a non-relativistic white dwarf), and solve the Lane-Emden equations for different values of ρ_0 (the central density of a star). For each ρ_0 you will get a mass and a radius. Make a mass-radius plot for this particular stellar model.

Task: Solve the TOV equation numerically for a polytropic equation of state with the n of your choice. Make a mass-radius plot for this case and compare with your previous mass-radius plot.

Task: Consider the effects of other equations of state

B Chaos in the double pendulum

B.1 Physical background

The simple pendulum is one of the first problems that you come across in undergraduate physics. However, it actually hides some quite complex physics behind it. In this project you will begin by investigating the motion of a simple pendulum beyond the small-angle approximation, and then move on to simulating a double pendulum. The latter system is especially interesting as it displays a phenomenon known as *chaos*.

B.2 Analytics to numerics

We first present you with the simple pendulum, which you are supposed to solve both analytically and numerically. This can be used to benchmark your numerical solver.

We then extend this to the double pendulum, which does not have a simple analytical solution and hence you have to fully rely on your numerical solver.

B.3 Problems with analytic solutions

The differential equation governing the motion of a simple pendulum is;

$$\frac{d^2\theta}{dt^2} + \frac{g}{l}\sin\theta = 0 \tag{4.9}$$

with the symbols defined in Fig. 4.1

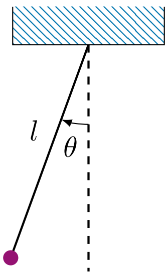

Figure 4.1: Simple pendulum

Task: Show that in the *small angle approximation*, the angle of the pendulum is described by

$$\theta(t) = \theta_0 \cos\left(\sqrt{\frac{g}{l}}t\right) \tag{4.10}$$

where θ_0 is the initial angle and the pendulum begins at rest.

B.4 Problems without simple analytic solutions

Now assume that the angle of the pendulum with respect to the vertical can take any value. This problem cannot be solved in terms of elementary functions[1].

Task: Numerically simulate the motion of a simple pendulum beyond the small-angle approximation. Can you find a value for the initial velocity which causes the pendulum to

[1] The solution comes out in terms of *elliptical integrals*, which have to be evaluated numerically anyway

stand up vertically? Compare your results to the exact expressions relevant to the small-angle approximation.

A more complicated and interesting problem is the double pendulum, where another pendulum is attached to the bottom of the first.

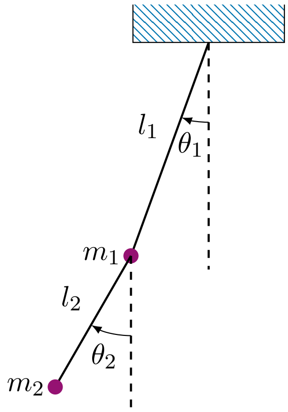

Figure 4.2: Double pendulum

The motion of a double pendulum is described by the following two coupled equations;

$$\begin{aligned} l_1 \Big[(m_1+m_2)\Big(g\sin(\theta_1)+\ddot{\theta}_1 l_1\Big)+\ddot{\theta}_2 l_2 m_2\cos(\theta_1-\theta_2)+\dot{\theta}_2^2 l_2 m_2\sin(\theta_1-\theta_2)\Big] &= 0 \\ l_2 m_2\Big[g\sin(\theta_2)+\ddot{\theta}_1 l_1\cos(\theta_1-\theta_2)+\dot{\theta}_1^2 l_1(-\sin(\theta_1-\theta_2))+\ddot{\theta}_2 l_2\Big] &= 0 \end{aligned} \tag{4.11}$$

where dots denote differentiation with respect to time.

Task: Numerically simulate the motion of a double pendulum for a range of initial conditions.

You should find that the motion of the double pendulum depends very sensitively upon the choice of initial conditions — this is one aspect of chaotic behaviour. In order to study this, you will create a *Poincaré section* for the two variables θ_2 and $\dot{\theta}_2$. The recipe for doing this is the following;

1. Pick initial conditions for θ_1 and $\dot{\theta}_1$. These will remain fixed for a given Poincaré section.
2. Pick an initial condition for θ_2 and $\dot{\theta}_2$.
3. Run your simulation, and record the times the inner pendulum passes through the vertical position ($\theta_1 = 0$) with a positive velocity.
4. For each time you recorded in the previous step, plot θ_2 against $\dot{\theta}_2$ as a point in the plane. You should let the simulation run long enough that you get enough points to see if there is any pattern.
5. Go back to step 2, picking a different initial condition with the same energy

Task: Create a Poincaré section for the double pendulum, and use this to identify different types of behaviour for different initial conditions.

C Dynamics of a wavepacket

C.1 Physical background: Schrödinger equation

In this project we will examine how a localised solution to the Schrödinger equation changes in space and time. This has applications in particle diffraction, tunnelling, the structure of atoms and many other places. The evolution of a wave function $\psi(\mathbf{r},t)$ describing a particle of mass m is governed by the Schrödinger equation;

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r})\right)\psi(\mathbf{r},t) = i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r},t) \tag{4.12}$$

where $V(\mathbf{r})$ is the potential. It will be convenient to work in a system of units where $m = 1$ and $\hbar = 1$, in which case the Schrödinger equation becomes;

$$\left(-\frac{1}{2}\nabla^2 + V(\mathbf{r})\right)\psi(\mathbf{r},t) = i\frac{\partial}{\partial t}\psi(\mathbf{r},t) \tag{4.13}$$

C.2 From analytics to numerics

We first present you with two wave packet problems that you are supposed to solve both analytically and numerically. These can be used to benchmark your numerical solver.

We will then present you with problems taken from real world applications that do not have a simple analytical solution and hence you have to fully rely on your numerical solver.

C.3 Problems with analytic solutions

Spreading of a free wave packet

We will initially work in one spatial dimension so that $\nabla^2 \to \frac{\partial^2}{\partial x^2}$ and $\psi(\mathbf{r},t) \to \psi(x,t)$, and assume that the wave function at time $t = 0$ is given a normalised Gaussian of width a, centred at the origin;

$$\psi(x,0) = \left(\frac{2a}{\pi}\right)^{1/4} e^{-ax^2} \tag{4.14}$$

and there is no external potential; $V = 0$. This can be done analytically by finding the Fourier transform of the initial wave function, considering each of the frequency components separately (for which we know the solutions to the Schrödinger equation), then applying the inverse Fourier transform to recover the wave function in real space. You can also do this in more than one dimension by repeating this process.

Free propagation of a wave packet

You can make the wave packet travel by including a factor e^{ik_0x} in the initial condition, and repeating the derivation above.

C.4 Problems without simple analytic solutions

The above route to analytic solution only works easily when $V = 0$. In general, one has;

$$\left(-\frac{1}{2}\frac{\partial^2}{\partial x^2} + V(x)\right)\psi(x,t) = i\frac{\partial}{\partial t}\psi(x,t) \tag{4.15}$$

which can be solved analytically in a few simple cases, but generally needs to be solved numerically. You should solve this equation numerically with $V = 0$, and compare your solution to the analytic one from the previous section. To do this;

- Approximate the Laplacian on the left-hand side using finite difference methods.
- Choose a time-stepping technique (e.g. Euler, leapfrog, Runge-Kutta, etc).
- Enforce some appropriate boundary conditions

In addition you should look for the following features

- In quantum mechanics the probability density $|\psi(x,t)|^2$ is conserved. Does this remain true in your numerical simulation?

The analytic solution in one dimension, as well as code you have written by this point, can both be fairly easily generalised to two spatial dimensions. You should therefore repeat the steps above but with an initial wave function given by

$$\psi(x,y,0) = \left(\frac{2a}{\pi}\right)^{1/4}\left(\frac{2b}{\pi}\right)^{1/4} e^{-ax^2-by^2} \tag{4.16}$$

which is a normalised Gaussian in two dimensions.

Now that you have a working code for propagation of a wave packet in one and two spatial dimensions, you can apply this to some situations of physical interest.

Tunnelling in one spatial dimension

Introduce a potential of the following form;

$$V(x) = \begin{cases} V_0 & \text{if } |x| < d/2 \\ 0 & \text{otherwise} \end{cases}. \tag{4.17}$$

This represents a potential barrier of width d and height V_0.

Task: Simulate the propagation of a wave packet from one side of this barrier to the other. What is the probability that a particle passes through the barrier as a function of its kinetic energy?

Single slit diffraction

Consider the following potential, defined in two spatial dimensions

$$V(x,y) = \begin{cases} \infty & \text{if } |x| < d/2 \text{ or } |y| > w/2 \\ 0 & \text{otherwise} \end{cases}. \tag{4.18}$$

This represents an infinitely high barrier with a slit of width w.

Task: Simulate the propagation of a wave packet through this slit. What is the probability that a particle is scattered by the slit at an angle θ with respect to the normal passing through the slit?

Collisions between wave-packets

Consider the two-particle Schrödinger equation

$$\left(-\frac{1}{2}\frac{\partial^2}{\partial x_1^2} - \frac{1}{2}\frac{\partial^2}{\partial x_2^2} + V(x_1, x_2)\right)\psi(x_1, x_2, t) = i\frac{\partial}{\partial t}\psi(x_1, x_2, t)\,. \tag{4.19}$$

Task: Use this and what you have learnt in the previous tasks to set up a numerical simulation of two colliding wave packets, using an inter-particle potential of

$$V(x_1, x_2) = V_0 e^{-\alpha|x_1 - x_2|^2}\,. \tag{4.20}$$

Part 5

Formalities

A The 22-point scale

The University's 22-point scale grades student work from A (Excellent) through to G (Very Poor) or H (no attempt). Within each band there are subdivisions; Table 5.1 shows these broad bands, the sub-bands, and the primary verbal descriptors that explain what they mean.

SCHEDULE A

Primary Grade	Gloss	Secondary Band*	Grade Point	Primary Verbal Descriptors for Attainment of Intended Learning Outcomes
A	Excellent	A1 A2 A3 A4 A5	22 21 20 19 18	Exemplary range and depth of attainment of intended learning outcomes, secured by discriminating command of a comprehensive range of relevant materials and analyses, and by deployment of considered judgement relating to key issues, concepts and procedures
B	Very Good	B1 B2 B3	17 16 15	Conclusive attainment of virtually all intended learning outcomes, clearly grounded on a close familiarity with a wide range of supporting evidence, constructively utilised to reveal appreciable depth of understanding
C	Good	C1 C2 C3	14 13 12	Clear attainment of most of the intended learning outcomes, some more securely grasped than others, resting on a circumscribed range of evidence and displaying a variable depth of understanding
D	Satisfactory†	D1 D2 D3	11 10 9	Acceptable attainment of intended learning outcomes, displaying a qualified familiarity with a minimally sufficient range of relevant materials, and a grasp of the analytical issues and concepts which is generally reasonable, albeit insecure
E	Weak	E1 E2 E3	8 7 6	Attainment deficient in respect of specific intended learning outcomes, with mixed evidence as to the depth of knowledge and weak deployment of arguments or deficient manipulations
F	Poor	F1 F2 F3	5 4 3	Attainment of intended learning outcomes appreciably deficient in critical respects, lacking secure basis in relevant factual and analytical dimensions
G	Very Poor	G1 G2	2 1	Attainment of intended learning outcomes markedly deficient in respect of nearly all intended learning outcomes, with irrelevant use of materials and incomplete and flawed explanation
H			0	No convincing evidence of attainment of intended learning outcomes, such treatment of the subject as is in evidence being directionless and fragmentary
CR	CREDIT REFUSED			Failure to comply, in the absence of good cause, with the published requirements of the course or programme; and/or a serious breach of regulations

* The Secondary Band indicates the degree to which the work possesses the quality of the corresponding descriptor.

† This gloss is used because it is the lowest grade normally associated with the attainment of an undergraduate award. Undergraduate students should be aware that progress to most honours programmes require a grade above D in certain courses. Postgraduate students should be aware that on most programmes an average above D in taught courses is required for progress to the dissertation at Masters level. Students should consult the appropriate degree regulations and course handbooks for the grades they require to progress to specific awards.

Table 5.1: The 22 point scale

B Absence and minimum requirements for the award of credit

University regulations require that students complete 75% of a course in order to receive credit for that course. For PHYS4029P, this means submitting work for at least 3 out of the 4 assessments.

B.1 Absence and non-submission of work

If you cannot submit your work on time, but have Extenuating Circumstances for this, you will not be penalised provided you follow the University's Extenuating Circumstances Policy. Guidance on this Policy follows. If you do need to record an Extenuating Circumstances Claim, please also send an email to the Lab Head explaining the situation.

How to submit an Extenuating Circumstances Claim

Submission of an Extenuating Circumstances claim is the mechanism that allows your circumstances to be considered by the Wellbeing Team. Please note all Extenuating Circumstances claims must be submitted within five working days of the date of the affected assessment. These can be logged for missed sessions, or sessions where you were present, but believe your ability to perform was hindered. In the latter case, students should note that the University's Code of Assessment allows grades to be awarded only on the basis of demonstrated work. So, if you feel that some piece of assessed work has been affected by adverse circumstances, and if staff agree, then the only course of action available is for the grade for that piece of work to be set aside (in the case of continuously assessed work and Class Tests) or to allow a resit (in the case of Degree Exams) – marks cannot be adjusted.

To submit an Extenuating Circumstances claim, you should fill in the form on the website.

Guidance and details of the process can be found here. If you encounter any difficulties with this process please contact the Lab Head immediately to let them know you have a problem with your Extenuating Circumstances claim.

B.2 Penalties for late submission

To quote from the policy:

"The University has agreed to introduce consistency in the penalties applied to penalties on students for late submission of coursework, and this has been warmly supported by the SRC. Following consultation, the following formula has been agreed: Work should be penalised at the rate of 2 Schedule A 'aggregation points' for each working day (or part day) by which it was submitted after the published deadline. This formula may be applied to a maximum of five working days; work submitted more than five days late should be awarded Grade H."

In the context of the current course, this means that for each working day (or part of a working day) after the deadline for the submission of a report for assessment, you will receive a deduction of 2 grade points on the 22 point scale from your assessed mark. Being a live performance, there is no way to submit a presentation after it was due.

C Plagiarism

Plagiarism is defined as the submission or presentation of work, in any form, which is not one's own, without acknowledgement of the sources. The University's degrees and other academic awards are given in recognition of the candidate's personal achievement. All suspected cases of plagiarism will be handled in accordance with the University Plagiarism Statement, which can be found at http://senate.gla.ac.uk/academic/plagiarism.html

In the context of this course, the above policy is not intended to stop you discussing your project work with other students – that's an essential part of group work after all. But when it comes to your individually assessed pieces of work, you must ensure that each report is written uniquely, whilst obviously referring at times to communally obtained results.

D Mapping of descriptors to 22-point scale

P3 Group Project Individual Report Mark and Feedback Sheet

University of Glasgow | School of Physics & Astronomy

Grade range (highest to lowest)	A1,A2,A3,A4,A5 (22-18)	B1,B2,B3 (17-15)	C1,C2,C3 (14-12)	D1,D2,D3 (11-9)	E1,E2,E3 (8-6)	F1,F2,F3 (5-3)	G1,G2,G3,H (<3)	Grade awarded
Descriptor	*Excellent*	*Very Good*	*Good*	*Satisfactory*	*Weak*	*Poor*	*G: Very Poor, H: No attainment*	
Presentation, Grammar, Style and Structure	Great presentation. Clear structure. Excellent English, both technically (grammar etc.) and stylistically.	Very good presentation, structure and English. Perhaps one or two minor deficiencies (e.g. typos, layout, text too small on graphs, figure captions).	Good presentation. Several smaller deficiencies as noted previously or one larger problem (e.g. graphs, structure or layout).	Presentation just about okay. But a lot of things that could be improved. The report is less attractive and less easy to follow as a result.	Big problems in presentation, structure or language. Does not look good to the reader, and is not easy to read.	Presentation is seriously messy, language is full of errors, structure is poor, and the layout is not well planned.	Little or no sign of any plan in the content and very difficult to make sense of the report because of the poor presentation.	
Abstract, Introductory Sections	Great abstract. The Introduction introduces the topic very well. And the theory and methods sections are comprehensive.	Very good start. Just one or two smaller problems, perhaps abstract too long or missing key points. Or introductory sections missing key information.	A good start to the report. A few smaller problems or one larger one, which makes these sections a little harder to follow than ideal.	A minimally okay start, but several shortcomings and not the clearest start to a report, nor the most informative to the group supervisor.	The start misses enough information, or doesn't build a logical sequence of steps so that it fails to really introduce the topic in a clear way.	The start is poorly written and doesn't really prepare the reader for the content at the core of the report.	Little or no content whatsoever, or little or none of any relevance to the topic.	
Main Part of Report	Excellent description of the work, including properly describing and discussion any figures and all analysis and calculations.	Very good results and discussion. Perhaps one or two minor shortcomings (e.g. too brief descriptions, missing analysis, discussion missing key points).	Good results and analysis. But several smaller weaknesses or one larger problem (e.g. insufficient discussion or description).	The sections are present, and the content is described there. Some analysis and discussion is present. But only the bare minimum.	Large omissions (e.g. important details missing, no text describing a result, no mathematical working or similar). This makes them hard to follow.	Lacking in any good quality presentation of results or discussion thereof. Some content, but not presented in any way that makes it easy for the reader to learn from.	Little or no content or relevant content in the results and discussion sections.	
Individual Contribution	Totally clear about personal contribution and how this added to the group work.	Very clear about personal contribution to the group, perhaps just minor deficiencies.	Good description of work, but maybe less clear about how this fits in the group as a whole.	Okay description of own contribution, but the larger context or reason for it is not so clear.	Content that is okay on its own but with little link to anything beyond this document.	Almost no sense of how this work was part of a group project.	No sense whatsoever that this was part of a team effort.	
Summary and Conclusions	Great summary, reiterating all key points of results and discussion, including on errors and their origins.	Very good summary. Perhaps one or two identifiable weaknesses (e.g. slightly longwinded, missing a key point).	Good summary. Most key stuff present. Perhaps several smaller things or one larger thing missing or faulty.	Summary is present and mostly does sum the report up. But not so clearly written and may miss significant points.	A weak summary that misses major points and is poorly structured, perhaps too short or rather too long.	A poor summary that does not make a large amount of sense.	Little or no summary, or one that contains little or no relevant content.	
Final Grade								

Project		Student Number		Marker	

P3 Group Project Group Report Mark and Feedback Sheet

University of Glasgow | School of Physics & Astronomy

Grade range (highest to lowest)	A1,A2,A3,A4,A5 (22-18)	B1,B2,B3 (17-15)	C1,C2,C3 (14-12)	D1,D2,D3 (11-9)	E1,E2,E3 (8-6)	F1,F2,F3 (5-3)	G1,G2,G3,H (<3)	Grade awarded
Descriptor	*Excellent*	*Very Good*	*Good*	*Satisfactory*	*Weak*	*Poor*	*G: Very Poor, H: No attainment*	
Presentation and Written Style	Great presentation. Excellent English, both technically (grammar etc.) and stylistically. Uses template very well.	Very good presentation and English. Perhaps one or two minor deficiencies (e.g. typos, layout, text too small on graphs, imperfect figure captions).	Good presentation. Several smaller deficiencies as noted previously or one larger problem (e.g. illegible graph or bad layout).	Presentation just about okay. But a lot of things that could be improved. The report is less attractive and less easy to follow as a result.	Big problems in presentation or language. Does not look good to the reader and is not easy to read.	Presentation is seriously messy; language is full of errors and the layout is not well planned.	Very poor presentation and quality writing making it difficult to understand or follow.	
Abstract, Introductory Section(s)	Great summary in the abstract. Introduction introduces the topic very well with an excellent critical review of the key literature.	Very good start to the report. Just one or two smaller problems, perhaps missing key points, or literature survey not comprehensive.	A good start to the report. Enough issues to make these introductory sections a little harder to follow than would be ideal.	A minimally okay start, but with several shortcomings so this is not the clearest start to a report, especially someone coming to the topic afresh.	Not enough information, or does not build a logical sequence of steps in the argument, so hard to really understand what the report is all about.	The start is poorly written and does not help a reader to go from a general knowledge of physics to understanding enough to appreciate the rest of the report.	Little or no content whatsoever, or little or none of any relevance to the topic in the heart of the report.	
Body of the Report	Excellent description of the work with good use of figures, high quality narrative and strong discussion.	Very good contents and discussion. Perhaps one or two minor shortcomings (e.g. too brief descriptions, missing analysis, errors not fully detailed, discussion missing key points).	Good results and analysis. But several smaller weaknesses or one larger problem (e.g. missing discussion of figures or missing content on a key point).	The sections are present, and results are there. Some analysis and discussion is present. But only the bare minimum, and the group really ought to have done more.	Large omissions or weakly written (e.g. important information or working missing, no text describing a result, as appropriate to that project). This makes it hard to follow.	Lacking in any good quality presentation of the work or discussion thereof. Perhaps some content, but not presented in any way that makes it easy for the reader to learn from.	Little or no content or relevant content in these sections.	
Summary and Conclusions	Great summary, reiterating all key points of the report succinctly and informatively.	Very good summary but with one or two identifiable weaknesses (e.g. slightly longwinded, missing a key point).	Good summary. Most key content present. Perhaps several smaller things or one larger thing missing or faulty.	Summary is present and mostly does sum the report up. But not so clearly written and may miss significant points.	A weak summary that misses major points and is poorly structured, perhaps too short or rather too long.	A poor summary that does not make a large amount of sense.	Little or no summary, or one that contains little or no relevant content.	
Integration / Structure	The report integrates the work of different subgroups well.	Slight jumps between the work of different contributors.	Noticeable deficiencies in integrating the work of all in the group.	A jumpy effect where the sections or paragraphs are not well linked.	Big problems such that the report looks like several stitched together.	Major structural problems and quite difficult to follow from one section to the next.	Little coherence at all in the sections within.	
Final Grade								

Project		Student Numbers		Marker	

P3 Group Projects Individual Talk Mark and Feedback Sheet

University of Glasgow | School of Physics & Astronomy

Grade range (highest to lowest)	A1,A2,A3,A4,A5 (22-18)	B1,B2,B3 (17-15)	C1,C2,C3 (14-12)	D1,D2,D3 (11-9)	E1,E2,E3 (8-6)	F1,F2,F3 (5-3)	G1,G2,G3,H (<3)	Grade awarded
Descriptor	*Excellent*	*Very Good*	*Good*	*Satisfactory*	*Weak*	*Poor*	*G: Very Poor, H: No attainment*	
Timekeeping and overall planning	Stuck perfectly to time. Excellent structure and totally clear.	Perhaps small deviations from time (1-2 mins) OR structure very good but with minor issues.	More than one small problem in structure and timekeeping, or one larger issue (e.g time missed by >2 mins)	Several significant issues with structure or timekeeping.	Poor timekeeping (either way too long or way too short) or weak structure.	Poor structure, and/or poor timekeeping showing little indication of any planning,	Little structure or planning of any sort in evidence resulting also in a poor use of the time.	
Quality of slides	Beautiful slides, with well laid out & clear text of appropriate sizes, in colours that promote legibility and with excellent figures.	Very good slides with just one or two marginal issues, e.g. text slightly small on slides or figures, or colour choices slightly less than optimal.	Good slides. Easy enough to read, even if there are some issues with layout, font sizes or colours/contrast.	Slides that are okay, but significantly less than perfect. Maybe layout messy, or some text too small, or contrast that makes legibility harder.	Somewhat messy slides with text that is too small, figures that are a bit difficult to read, and maybe odd colour choices that detract from ease of reading.	Messy slides that are difficult to read and do not present the information well at all, for whatever reason (layout, planning, text sizes, colours/contrast).	Few slides, or very messy ones with little relevant content.	
Clarity of Oral Presentation	Clear speaking, and direct to the audience in a way that engages them well.	Very good oral presentation, but perhaps with minor issues (e.g. less engaging delivery, not facing camera).	Good oral presentation but with some issues (e.g. audibility/clarity, or not looking at the audience enough)	OK oral performance, and understandable, but not great or really engaging.	Significant deficiencies, perhaps hard to hear, or very monotonic delivery, or really doesn't look at the camera.	Bad delivery. Maybe mumbling and difficult to understand, and not really engaging in any way at all.	Little or nothing that makes any sense in anything said.	
Content	Excellent scientific content. Clear evidence that they did some great work and that this contributed to good progress on project.	Very good scientific content. Maybe some minor questionable things, or not perfectly clear how it fitted inside the work of the group.	Good scientific work. Perhaps some things not so perfectly understood or reported. Maybe some context missing.	OK work. Clear that they did do some work of some value to the group. But reporting is maybe patchy and incomplete, or errors are easily visible.	Less than satisfactory. Whilst work has been done for the group, the usefulness or correctness is unclear or questionable.	Limited scientific content of any value, and far less than would be expected at this point.	Little or no correct and relevant content to the work of the group. Questionable as to whether the student is doing anything useful.	
Answers to Questions	Clear, competent and well-informed answers to questions.	Very good answers to questions, although possibly with minor shortcomings.	Good answers to questions but showing evidence of gaps in knowledge.	Minimally acceptable answers, at least showing understanding of the question, even if answers somewhat lacking.	Weak answers to questions, and at a level below expectations at this point in student career.	Poor answers, demonstrating little understanding of either the question nor of the work performed in the project.	Little or nothing in the way of a useful answer to any question.	
Final Grade								

Project		Student Number		Marker	

P3 Group Projects Group Talk Mark and Feedback Sheet

University of Glasgow | School of Physics & Astronomy

Grade range (highest to lowest)	A1,A2,A3,A4,A5 (22-18)	B1,B2,B3 (17-15)	C1,C2,C3 (14-12)	D1,D2,D3 (11-9)	E1,E2,E3 (8-6)	F1,F2,F3 (5-3)	G1,G2,G3,H (<3)	Grade awarded
Descriptor	*Excellent*	*Very Good*	*Good*	*Satisfactory*	*Weak*	*Poor*	*G: Very Poor, H: No attainment*	
Timekeeping and overall planning	Stuck perfectly to time. Excellent structure and totally clear.	Perhaps small deviations from time (1-2 mins) OR structure very good but with minor issues.	More than one small problem in structure and timekeeping, or one larger issue (e.g time missed by >2 mins)	Several significant issues with structure or timekeeping.	Poor timekeeping (either way too long or way too short) or weak structure.	Poor structure, and/or poor timekeeping showing little indication of any planning,	Little structure or planning of any sort in evidence resulting also in a poor use of the time.	
Quality of slides	Beautiful slides, with well laid out & clear text of appropriate sizes, in colours that promote legibility and with excellent figures.	Very good slides with just one or two marginal issues, e.g. text slightly small on slides or figures, or colour choices slightly less than optimal.	Good slides. Easy enough to read, even if there are some issues with layout, font sizes or colours/contrast.	Slides that are okay, but significantly less than perfect. Maybe layout messy, or some text too small, or contrast that makes legibility harder.	Somewhat messy slides with text that is too small, figures that are a bit difficult to read, and maybe odd colour choices that detract from ease of reading.	Messy slides that are difficult to read and do not present the information well at all, for whatever reason (layout, planning, text sizes, colours/contrast).	Few slides, or very messy ones with little relevant content.	
Clarity of Oral Presentation	Clear speaking, and direct to the audience in a way that engages them well.	Very good oral presentation, but perhaps with minor issues (e.g. less engaging delivery, not facing camera).	Good oral presentation but with some issues (e.g. audibility/clarity, or not looking at the audience enough)	OK oral performance, and understandable, but not great or really engaging.	Significant deficiencies, perhaps hard to hear, or very monotonic delivery, or really doesn't look at the camera.	Bad delivery. Maybe mumbling and difficult to understand, and not really engaging in any way at all.	Little or nothing that makes any sense in anything said.	
Content	Excellent scientific content. Clear evidence of great work in the project. Good integration of all sections.	Very good scientific content. Maybe some minor questionable things, or imperfect integration of the different parts of project.	Good scientific work. Perhaps some things not so perfectly reported. Maybe some context missing, or parts not connected.	The work is just OK. But reporting is maybe patchy and incomplete, errors are easily visible, or the presentation is seriously disjointed.	The content is less than satisfactory. The usefulness or correctness of the work reported is questionable and/or the content is disconnected.	Limited scientific content of any value, and far less than would be expected at this point, and the presentation is disjointed and messy in contents (not just style).	Little or no correct and relevant scientific content in the presentation, and any information very disconnected.	
Answers to Questions	Clear, competent and well-informed answers to questions.	Very good answers to questions, although possibly with minor shortcomings.	Good answers to questions, but showing evidence of gaps in knowledge.	Minimally acceptable answers, at least showing understanding of the question, even if answers somewhat lacking.	Weak answers to questions, and at a level below expectations at this point in student career.	Poor answers, demonstrating little understanding of either the question nor of the work performed in the project.	Little or nothing in the way of a useful answer to any question.	
Final Grade								

Project		Student Numbers		Marker	

Revision History

Revision	Date	Author(s)	Description
1	Dec 9, 2025	Sophie Renner	Initial 2025/2026 version